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Museum of Northern Arizona, Springs Stewardship Institute
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Springs Inventory and Assessment Training Manual

Springs Inventory and Assessment Protocols
Version 3.0

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1 Introduction to Springs Ecosystems

Springs Ecology and Stewardship

Springs are ecosystems where groundwater is exposed at, and typically flows from the Earth's surface (Fig. 1–1). Academically described as "groundwater-dependent surface-linked headwater wetland ecosystems," here we will just refer to them as springs. In our experience, spring sources are usually multiple; therefore, we refer to these features in the plural form as "springs" or "springs ecosystems".

Fed by groundwater aquifers, springs occur in many settings, both underwater and in terrestrial environments. Springs vary greatly in flow rate, water chemistry, geomorphic form, ecological significance, and cultural and economic importance (Springer et al. 2008, Springer and Stevens 2009). Seeps are simply small springs, usually with immeasurably diffuse or small seepage.

While more obviously important in arid regions, springs are among the most productive and influential ecosystems in all landscapes. Springs serve as hydrogeologic windows into aquifers (Töth and Katz 2006, Kresic and Stevanovic 2010, Springer et al. 2015), critical water supplies, keystone ecosystems (Perla and Stevens 2008), refugia for rare or unique species (e.g., Shepard 1993; Scarsbrook et al. 2007; Hershler et al. 2014, 2015), remarkable paleontological repositories, and socio-economical focal points of human culture and development (Stevens and Meretsky 2008, Gleick 2010, Scott 2014).

Until recently, scientific research has been insufficient to understand springs form and function as socio-ecosystems, or to develop coherent, integrated inventory and data management protocols. Short-term springs studies and research projects have been conducted (reviewed in Danks and Williams 1995, Botosaneanu 1998, Stevens and Meretsky 2008), and hydrological studies of springs have focused on the delivery of groundwater to the surface (Springer and Stevens 2009, Hershey et al. 2010), but few studies have been conducted on springs as ecosystems. To our knowledge, only three springs complexes in the United States have been studied and monitored in sufficient detail to provide insight into ecosystem function and change over time: Silver Springs in Florida (Odum 1957, Munch et al. 2006); Montezuma Well in central Arizona (Blinn 2008); and

Fig. 1–1. Mary Jane Falls Spring is located in the Spring Mountains National Recreation Area, Clark County, Nevada.

Yellowstone National Park hot springs (Brock 1994). Additional springs ecosystem studies are underway, and improved understanding of springs ecosystem ecology will continue to influence inventory issues and techniques.

Conceptual Model

Stevens and Springer (2004) proposed a general conceptual model of springs ecosystems (Fig. 1–2) It is a primarily bottom-up model of springs ecosystems with external physical variables such as climate and aquifer driving local physical variables such as geomorphology, microclimate, flow and water chemistry, and the disturbance regime. These local physical variables together define the microhabitats at the site, which in turn shape biotic interactions. At the same time, human use exerts top-down influences on all levels of the model.

While not yet fully tested and quantified, this springs ecosystem model forms the conceptual framework around which the Springs Inventory Protocol was designed. Following this bottom-up dynamic, surveyors record data on a variety of local physical variables including flow, water chemistry, local geomorphology and soils; use that information to define and map microhabitats; and document the vegetation community according to microhabitat affiliation. Surveyors also record wildlife use of the site with notes on specific habitat use. Evidence of recent, historic, and prehistoric human use of the site (the model's top-down component) is carefully described as well. This primarily bottom-up model also

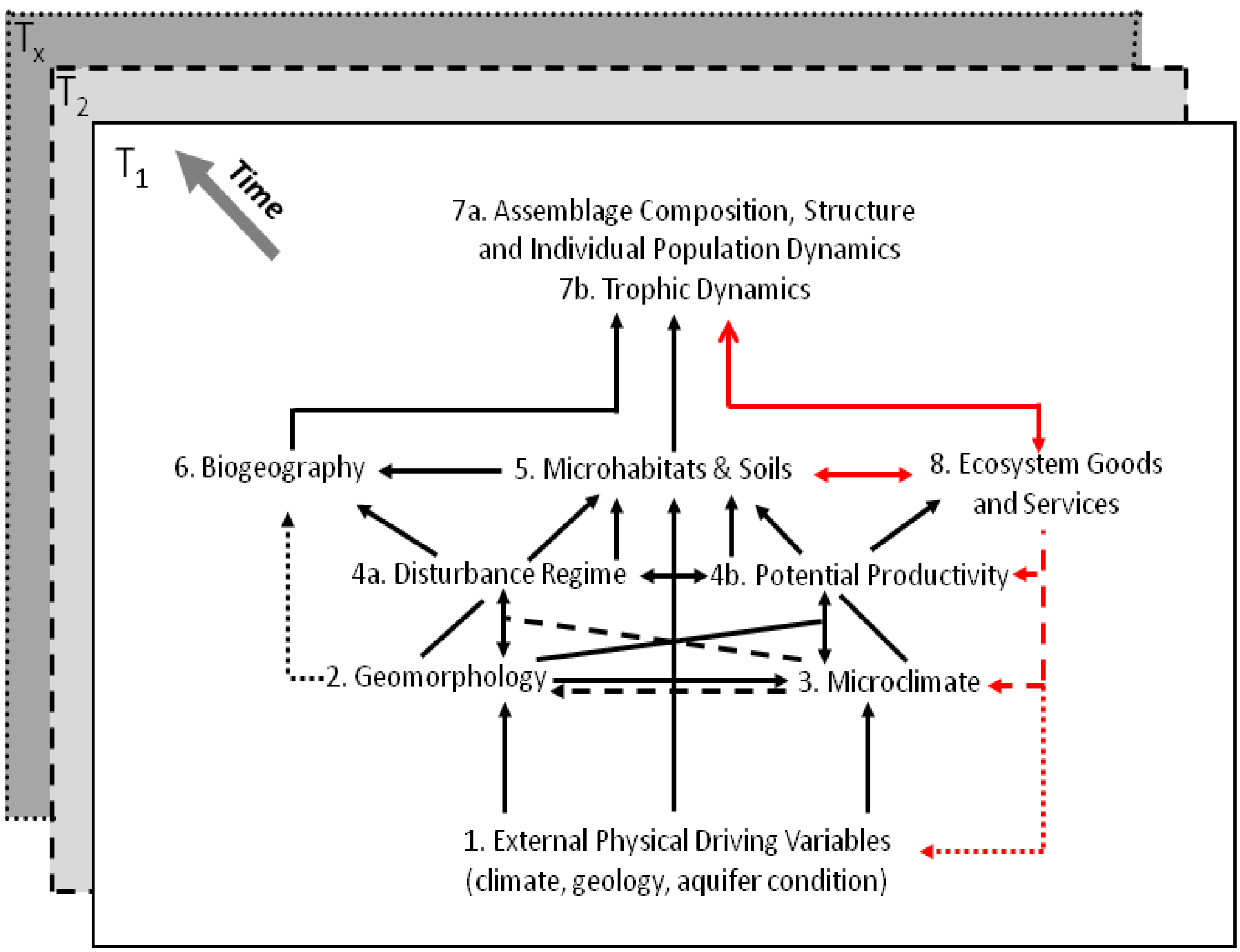

Fig. 1–2. Springs ecosystem conceptual model (modified from Stevens and Springer 2004). Dashed arrows reflect indirect influences, while red arrows indicate human impacts.

supports the use of site geomorphology as the primary factor in the Springer and Stevens (2009) springs classification system (described below). In addition to providing a conceptual foundation for the springs inventory methods and springs classification system, the model may also be used to inform springs ecosystem assessment, stewardship activities, and monitoring.

Springs Classification

Improved stewardship of springs requires a definitive classification system because springs ecohydrology, management, development, and restoration options all vary in relation to springs type (Kreamer et al. 2015, Stevens et al. 2016, Sinclair 2018). Identification of rare springs, systematic assessment of ecological integrity, variation in microhabitat distribution, and the distribution of rare, endemic or endangered springs-dependent species all are central natural resource management concerns that require knowledge of the springs type. Springs are highly individualistic ecosystems which vary widely in many features, and a definitive, widely accepted global springs classification system is essential to improve basic scientific understanding and ecosystem stewardship.

The history of springs classification extends back more than a century, with attempts to classify springs by Fuller (1904), Thienemann (1907, 1922), Keilhack (1912), Waring (1915), Bryan (1919), Meinzer (1923), Clarke (1924), and Stiny (1933). Meinzer (1923) identified 11 different suites of variables through which to classify springs, and various authors have proposed other useful classification schemes (see Glazier 2009 for a summary of 46 such schemes). These can be grouped into seven general conceptual approaches, including those focused on characteristics of:

1) the aquifer
2) springs discharge
3) water quality (temperature, geochemistry)
4) landscape position
5) local site geomorphology
6) vegetation
7) combinations of those variables

All of these approaches (reviewed in Springer and Stevens 2009) have their respective merits, but the most widely used and definitive approach to classifying springs ecosystem types is through geomorphology.

Springer et al. (2008) and Springer and Stevens (2009) expanded the early geomorphological characterization to include 12 discrete types of terrestrial springs, not including fossil paleosprings (i.e., springs that flowed in the non-recent geologic past, but no longer flow). Now, after more than a century of springs, stream, and wetland classification efforts, the only definitive geomorphic classification system for springs is that of Springer and Stevens (2009), summarized here.

A Key to Springs Types

The springs types described in the key (Table 1–1) are based on revision of the Springer and Stevens (2009) classification system. The dichotomous key was developed by examination of more than 1,500 springs throughout the New World. While 13 primary springs types are described here, note that nearly all types of springs can be created through anthropogenic action, or have substantial anthropogenic attributes; springs in these situations would be labeled with the subtype "anthropogenic." Common examples of anthropogenic springs range from livestock tanks, springs altered by diverting or piping flow from the original source, springboxes that have obliterated the natural source, and hot springs resorts. This key has been tested by colleagues and associates, both those familiar and unfamiliar with springs inventory classification.

Description of Springs Types

On the pages following the dichotomous key, we provide a description of each of the spring types identified by Springer and Stevens (2009. These descriptions include a diagram, example photo, common springs subtypes, alternate names, and common stressors.

Table 1–1. A dichotomous key to terrestrial springs types (adapted from Stevens et al. 2020). All springs can have more than one springs type, and all springs types can be perennial or ephemeral (i.e., secondarily hypocrene).

1	Groundwater expression of flow is subterranean, emerging within a cave (a water passage, often through limestone or basalt), before emerging into the atmosphere or subaqueously into a surface pool or channel. Lentic (standing or slow-moving) and/or lotic (fast-moving) flow conditions can exist.	Cave Spring
	Groundwater expression of flow emerges or emerged in a subaerial setting (in direct contact with the atmosphere), including within a sandstone alcove or subaqueously (beneath a body of water), but not from within a cave. Lentic and/or lotic flow conditions can exist.	2
2	Groundwater is not expressed at the time of visit (the springs ecosystem is not flowing; the soil may be dry or moist, but not saturated).	3
	Groundwater is expressed at the time of visit; saturation, seepage, and/or flow are actively expressed (water and/or saturated soil are evident); Lentic and/or lotic flow conditions can exist.	5
3	Evidence of prehistoric groundwater presence and/or flow exists (e.g., paleotravertine, paleosols, fossil springs-dependent species, etc.), but no evidence of contemporary flow or aquatic, wetland, or riparian vegetation.	Paleospring
	Not as above.	4
4	Soil is dry or moist but is not saturated by groundwater. Groundwater is expressed solely through wetland or obligate riparian vegetation.	Hypocrene Spring
	Groundwater is expressed through saturated soil, or as standing or flowing water. Lentic and/or lotic flow conditions can exist.	5
5	Groundwater is expressed, but discharge is primarily lentic (standing or slow-moving), and flow downstream from the springs ecosystem may be absent or very limited.	6
	Groundwater is expressed; discharge is primarily lotic (fast-moving) and flows actively within and/or downstream, away from the springs ecosystem.	11
6	Groundwater is expressed as a patch of shallow standing water or saturated fine sediment or soil, usually strongly dominated by hydric soils and emergent herbaceous wetland vegetation, but sometimes can include woodland or forest vegetation (e.g., palm oases, swamp forests). The slope is usually low (<16°). These sites are colloquially called wet meadows or ciénegas and include some GDE fens. Lotic flow conditions prevail.	7
	Subaqueous flow creates an open, lentic body of water, typically more than a few square meters in area, not dominated by emergent wetland vegetation, and with or without outflow.	8
7	A wet meadow with seepage emerging from the margin of an active surface flow-dominated channel or floodplain, and subject to regular flood scour by the stream channel into which it feeds.	Helocrene; secondarily Rheocrene
	A wet meadow with seepage emerging outside and away from an active surface flow-dominated channel or floodplain, and not subject to regular flood scour by a stream.	Helocrene
8	The groundwater table surface is exposed as a pool with standing water, without a focused inflow source, and with no outflow. Lotic flow conditions exist. Many prairie pothole springs are classified as this springs type.	Exposure
	A pool is formed by one or more focused, usually subaqueous, inflow sources; generally with outflow, if not frozen.	9

9	Springs source is surrounded by, and has contributed to the formation of, a mound composed of chemical precipitate (e.g., travertine), ice, or organic matter. Both lentic and lotic flow conditions can occur.	10
	Springs source forms an open pool which is not surrounded by a springs-created mineral, ice, or organic mound; often with a focused outflow channel. Lentic flow conditions prevail, but lotic flow may occur in the outflow channel.	Limnocrene
10	Springs source is surrounded by, and/or emerges from a mound composed of carbonate (including travertine) or other chemical precipitate. Both lentic and lotic flow conditions can occur.	Mound-form (Carbonate)
	Springs source is surrounded by, and/or emerges from a mound composed of ice in an ice-dominated landscape. Flow may be seasonal, and both lentic and lotic flow conditions can occur. Also colloquially called pingos or aufeis springs.	Mound-form (Ice)
	Springs source is surrounded by, and/or emerges from a mound composed of organic matter, such as decomposing vegetation or peat. Lentic flow conditions generally prevail. Some GDE fens are classified as this springs type.	Mound-form (Organic)
11	Springs flow emerges explosively and periodically, either by geothermally-derived or gas-derived pressure. Lotic flow conditions generally prevail. This springs type includes geothermal geysers and "coke-bottle" (CO2 gas-driven) geysers.	Geyser
	Springs flow emerges non-explosively, but by the action of gravity.	12
12	Artesian flow emerges from one or more focused points and rises 10 cm or more above ground level due to gravity-driven head pressure. After the flow falls to the ground, lentic or lotic flow conditions may prevail. Colloquially called artesian springs.	Fountain
	Springs flow may emerge from a focused point, but without substantial artesian rise above ground level.	13
13	Springs flow emerges from a bedrock cliff and not within an established surface flow channel (although a surface flow channel may exist on top of the cliff, directly above the source).	14
	Not as above.	15
14	Focused lotic flow emerges from a bedrock cliff and immediately cascades, usually as a madicolous sheet of whitewater flow, down the cliff face.	Gushet
	Flow emerges along a horizontal geologic contact, typically dripping along a seepage front and often creating a wet backwall. This springs type includes unvegetated or vegetated seepage patches on near vertical or overhung bedrock walls. Both lentic and lotic flow conditions can occur.	Hanging Garden
15	Flow emerges from a surface flow-dominated channel bed. Upstream of the spring source, the channel may be a perennial stream or it may be dry. Lotic flow conditions generally prevail. These springs are subject to channel flood scour.	Rheocrene
	Flow emerges from a non-bedrock dominated slope that does not have a surface flow channel upslope of the springs source. Sources may emerge within an upland habitat or a floodplain, but not within the bed of a surface flow channel. In some cases, these springs may emerge from the base of a cliff, but not from the cliff itself. Lotic flow conditions generally prevail.	16
16	Flow emerges from a 16-60° slope in an uplands habitat, not associated with a floodplain or channel that is subject to regular surface flow stream flood scouring.	Hillslope
	Flow emerges from the bank or terrace of an active riparian channel or floodplain and the source is subject to regular flood scour by the stream into which it feeds.	Hillslope; secondarily Rheocrene

Springs Ecosystem Types and Descriptions

Cave

Definition: Groundwater emergence within a cave, from tubular, fissure, or joint geologic structure (Fig. 1–3; Meinzer 1923; Fetter 2001).

Common Attributes and Secondary Types: Can be perennial or ephemeral; anthropogenic subtype is possible (Fig. 1–4).

Alternate Names and Comments: In-aquifer spring; karstic spring; cavern springs

Common Stressors: Groundwater extraction, pollution, and recreation.

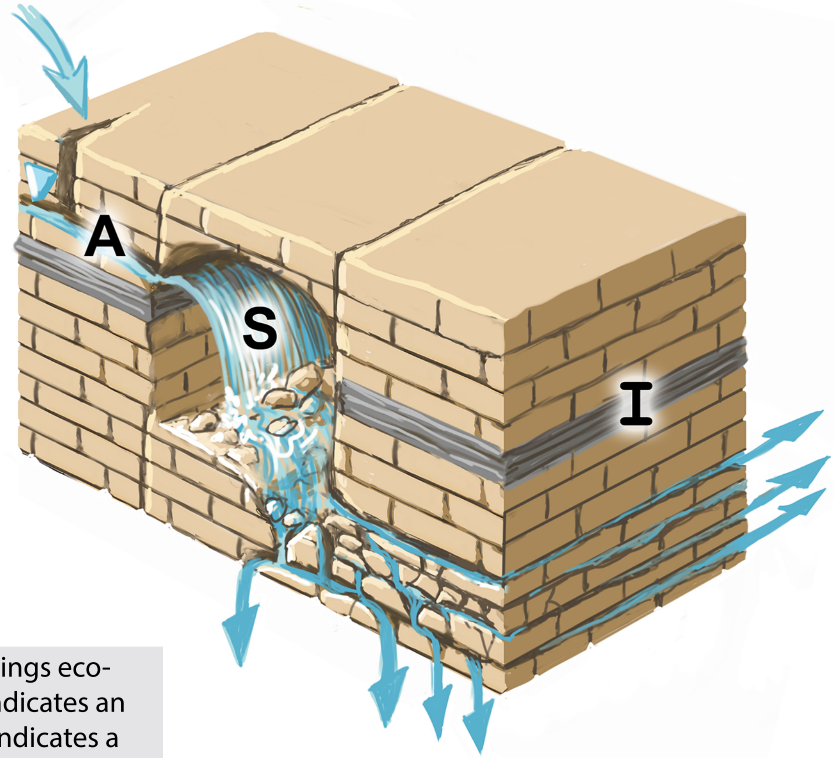

Fig. 1–3. In this illustration of a cave springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist.

Fig. 1–4. Pivot Rock Springs, a cave emergence spring in Coconino National Forest, Arizona. This spring has been modified with a constructed dam that forms a pool.

Exposure

Definition: The groundwater is exposed to the atmosphere, but typically does not flow (Fig. 1–5). These gravity water bodies occur in fracture, contact, or depression structural contexts (Meinzer 1923; Fetter 2001).

Common Attributes and Secondary Types: This springs type is perennial by definition; anthropogenic subtype can be created by mines, livestock watering tanks, road cuts, etc.

Alternate Names and Comments: In-aquifer, cavern, or fissure springs (Fig. 1–6).

Common Stressors: Groundwater extraction, pollution, recreation, filling/dredging, non-native species introduction, and climate change.

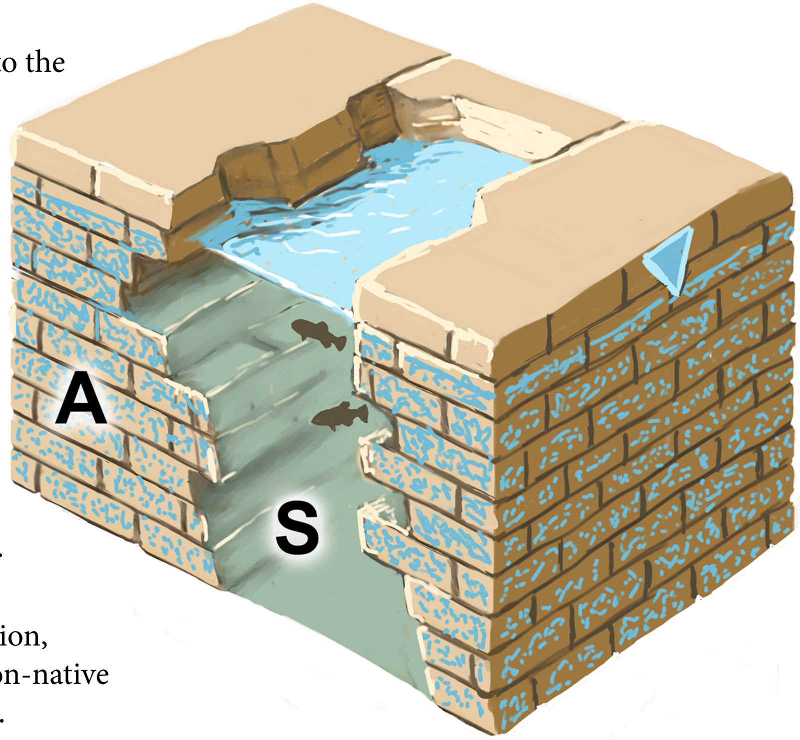

Fig. 1–5. In this illustration of an exposure springs ecosystem, "A" indicates aquifer input and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona, Springs Stewardship Institute and Victor Lesyk, artist. All rights are reserved.

Fig. 1–6. Devils Hole, an exposure spring located at Ash Meadows National Wildlife Refuge, Nevada. This warm spring is best known for serving as habitat for the only wild population of the endangered Devil's Hole Pupfish. Photo courtesy of U.S. Fish and Wildlife Service.

Fountain

Definition: An artesian upwelling of groundwater in a fracture or tubular geologic structural setting which forces flow to rise higher than the surrounding landscape (Fig. 1–7; Meinzer 1923).

Common Attributes and Secondary Types: This springs type can be ephemeral or perennial; an anthropogenic subtype can be created by drilling into an artesian aquifer (Fig. 1–8 and Fig. 1–9).

Common Stressors: Groundwater extraction, pollution, livestock water supplies, recreation, non-native species introduction, and climate change.

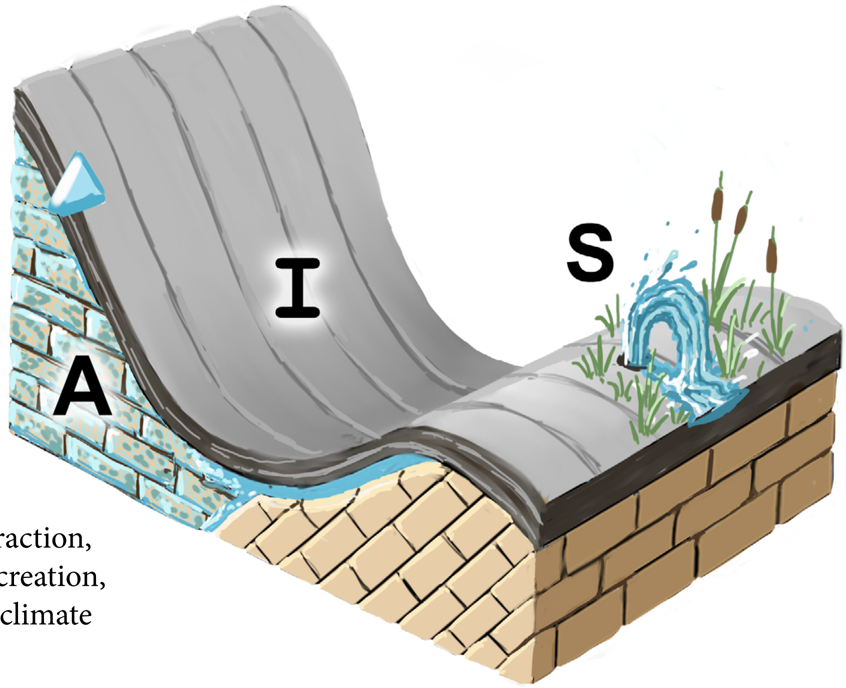

Fig. 1–7. In this illustration of a fountain springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist.

Fig. 1–8. Fence Fault Bidet on the bank of the Colorado River in Grand Canyon National Park.

Fig. 1–9. "Vulcans Bidet" is a fountain spring that emerges at Colorado River Mile 181 on the left in Grand Canyon National Park, Arizona. The spring is covered during high flows.

Geyser

Definition: Characterized by periodic discharge eruptions, groundwater is forcibly ejected by geothermal water (steam) or other gas, often from a precipitate mound (Fig. 1–10).

Common Attributes and Secondary Types: This springs type is by definition ephemeral, due to the periodicity of eruptions; an anthropogenic subtype can be created through well drilling into geothermal or CO_2-producing strata and aquifers (Fig. Fig. 1–11).

Common Stressors: Groundwater extraction, recreation, non-native species introduction, and climate change.

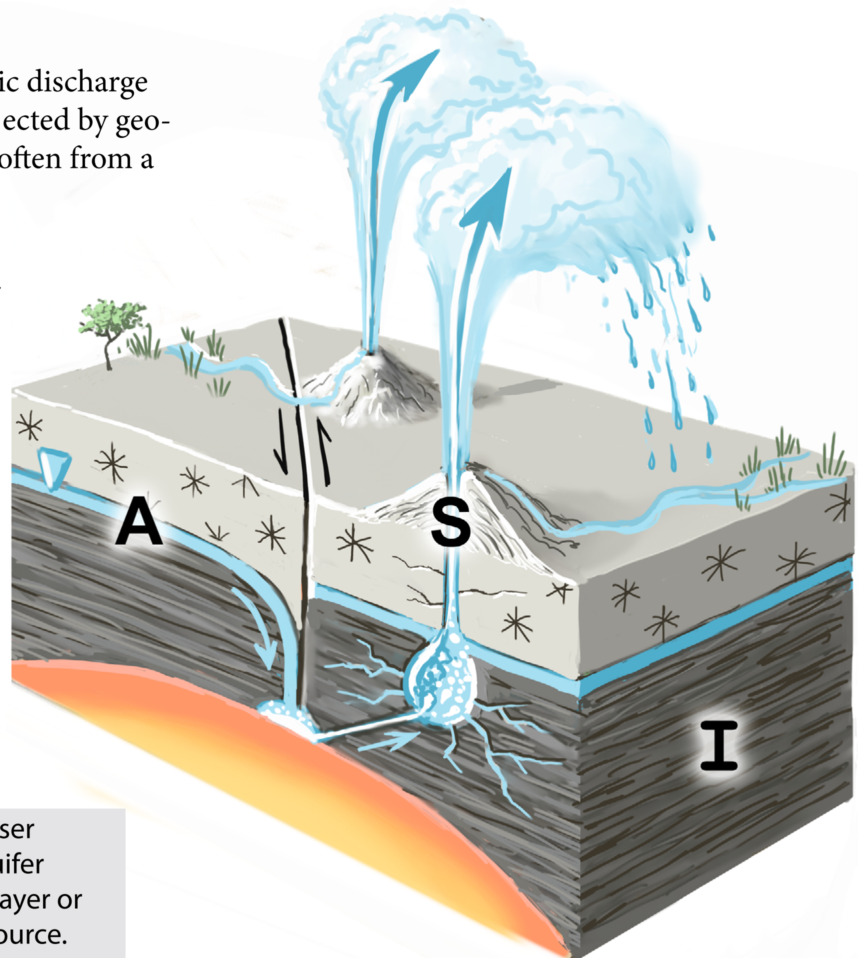

Fig. 1–10. In this illustration of a geyser springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Fig. 1–11. Crystal Geyser, near Green River, Utah. At this anthropogenic geyser, hydraulic eruptions are driven by carbon dioxide gas.

Gushet

Definition: Groundwater emerges and cascades in madicolous flow down a nearly vertical cliff (Fig. 1–12 and Fig. 1–13).

Common Attributes and Secondary Types: Common subtypes associated with this springs type are cave, hillslope, mound-form, rheocrene.

Alternate Names and Comments: Fracture, fissure, joint, or cliff springs.

Common Stressors: Groundwater and surface water extraction, livestock water supplies, recreation, non-native species introduction, and climate change.

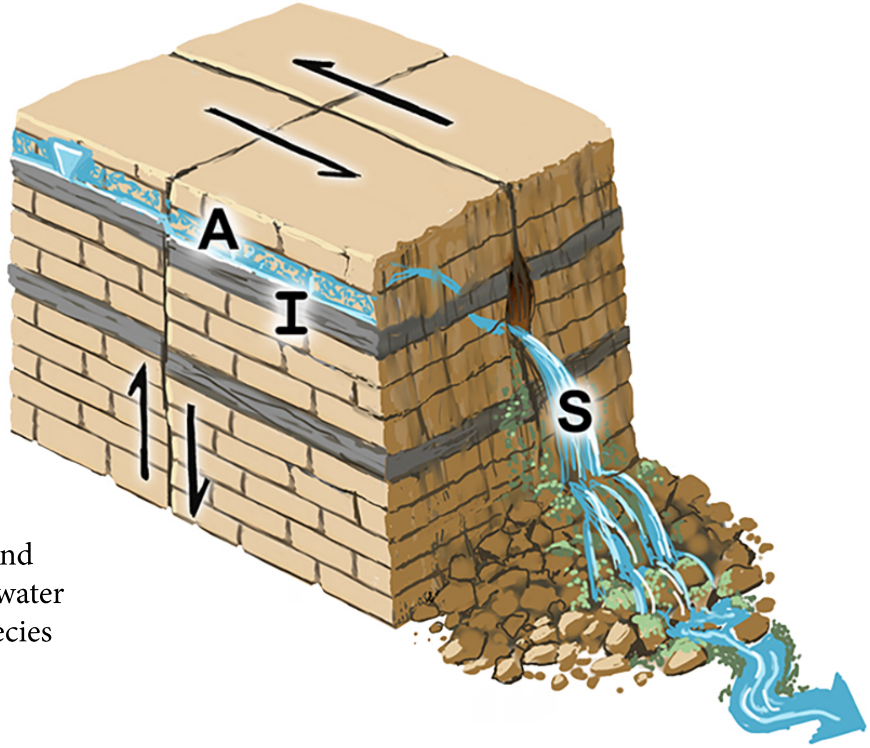

Fig. 1–12. In this illustration of a gushet springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Fig. 1–13. Vaseys Paradise in Grand Canyon National Park, Arizona is a gushet.

Hanging garden

Definition: Contact emergence from a horizontally bedded aquifer (often sandstone or basalt) that overlies an aquitard (Fig. 1–14 and Fig. 1–15).

Common Attributes and Secondary Types: Can be perennial or ephemeral; common subtypes associated with this springs type are hillslope, mound-form, and rheocrene; anthropogenic subtype is possible; for example, cliff seepage downstream from dams (Fig. 1–16).

Alternate Names and Comments: Seepage area or contact spring (Bryan 1919, Meinzer 1923); contact and fracture or fracture zone system (Bryan 1919); cliff spring.

Common Stressors: Groundwater and surface water extraction, livestock water supplies, recreation, non-native species introduction, and climate change.

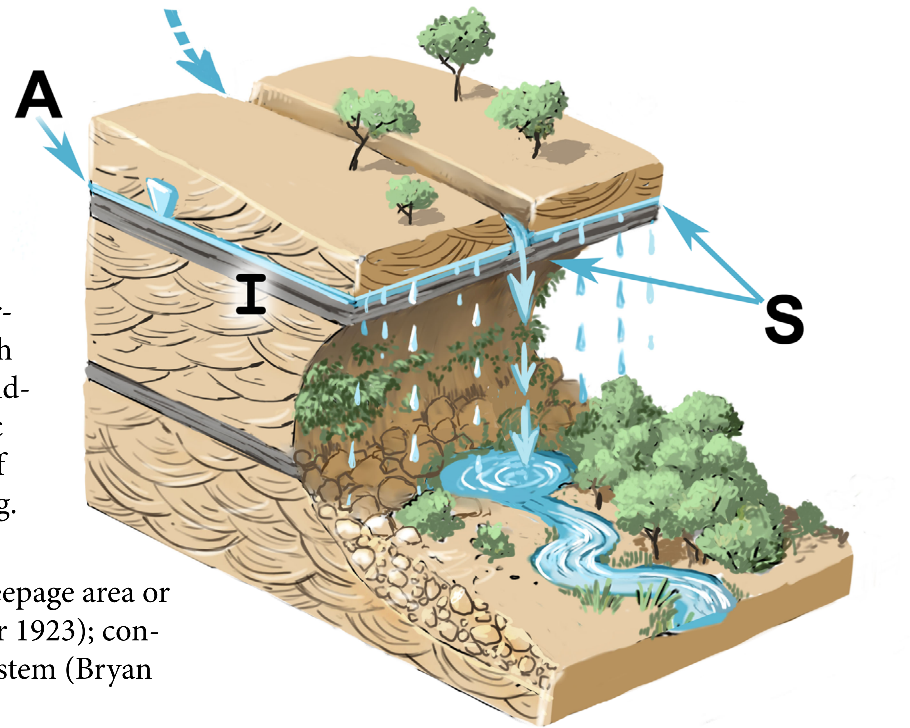

Fig. 1–14. In this illustration of a hanging garden springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Fig. 1–15. Whale's Armpit, a hanging garden located in Grand Canyon National Park, Arizona.

Fig. 1–16. This classic hanging garden emerges above the Colorado River along a geologic contact in Glen Canyon National Recreation Area.

Helocrene

Definition: Low-gradient, marsh-forming, gravity-driven wet meadow springs ecosystem (Fig. 1–17). This springs type is characterized by non-focused seepage flow that arises from a contact or seepage geologic setting (Fig. 1–18 and Fig. 1–19).

Common Attributes and Secondary Types: This springs type can be ephemeral or perennial. Many helocrene springs are alkaline.

Alternate Names and Comments: Wet meadows, ciénegas (when below 2,000 m elevation (Meinzer 1923); GDE fens; palustrine marshes; emergent and scrub-shrub wetlands; sinkholes; Pleistocene lakebed wetlands if groundwater expressed at surface; wet slack (when ephemeral); ephemeral GDE marshes (Boulton 2005); dispersed flow wetlands; mires (multiple subclasses); monsoon-driven or snowmelt-driven ephemeral slope wetlands; mineral-rich peatlands (noted for endemic species).

Common Stressors: Groundwater extraction, livestock water supplies (creation of open water), agricultural hay-mowing, urbanization, road construction (may dewater the downslope portion), peat mining, recreation, non-native species introduction, and climate change.

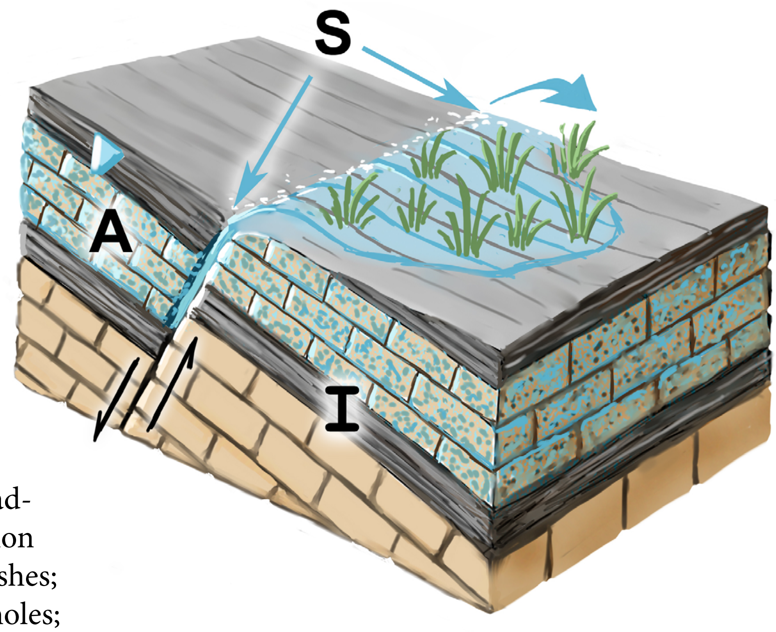

Fig. 1–17. In this illustration of a helocrene springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Ciénegas

The American Southwest contains groundwater dependent ecosystems called ciénegas. These are helocrenic, and sometimes secondarily rheocrenic, low-gradient springs that support freshwater wet meadows and are located at elevations below approximately 2,000 m. The centers of ciénegas are too wet to support trees and are composed of wetlands grasses, sedges, rushes, and forbs in a highly organic soil.

Ciénega margins often contain typical riparian trees including Gooding's willows and cottonwoods. Nearly half of these unique wetland features in the contiguous U.S. are found in New Mexico, with most of the remainder found in neighboring Arizona and Sonora (Cole and Cole 2015).

Many ciénegas are highly impaired by channel incision, watering tank berms, roadways, and groundwater drawdown (Minckley and Brunelle 2007). Less than half are considered unimpaired or in a near natural state. Inventorying and assessing these ecosystems is especially important due to the number of ciénegas that are already impaired, destroyed, or at risk of impairment.

Fig. 1–18. Faywood Warm Ciénega, in Grant County, New Mexico. Ciénegas are unique subtypes of helocrene springs, found only in the American Southwest.

Fig. 1–19. Pinnacle Cienga, located in Grand Staircase Escalante National Monument, Utah.

Hillslope

Definition: Groundwater emergence via gravity on relatively steep 16°-60° slopes, with diffuse or focused flow (Fig. 1–20). Flow is most often diffuse at the top of the springs and more focused at the bottom of the spring. Hillslope springs often support a wide array of wetland and riparian vegetation associations; when hillslope springs are travertine-forming, there is often an associated bryophyte (moss) community.

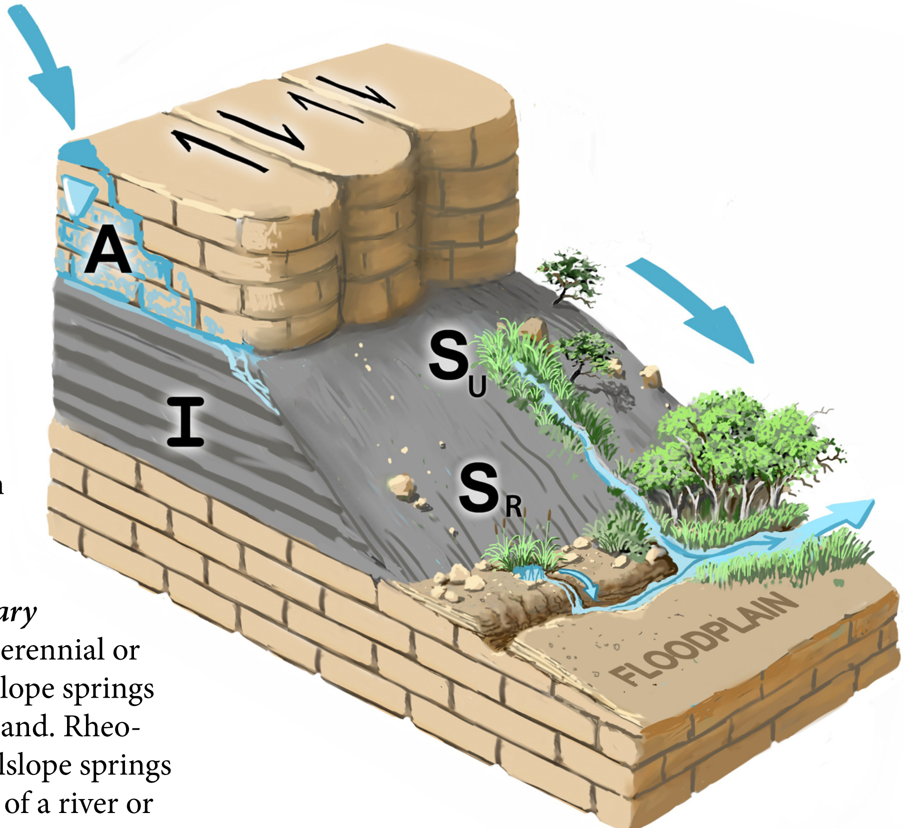

Fig. 1–20. This illustration of hillslope springs shows both an upland hillslope spring and a rheocrenic hillslope spring. "A" indicates aquifer input and "I" indicates an impermeable layer or aquitard. "S_U" marks the springs source of an upland hillslope spring, while "S_R" marks a rheocrenic hillslope springs source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Common Attributes and Secondary Types: Hillslope springs can be perennial or ephemeral. Two subtypes of hillslope springs are common: rheocrenic and upland. Rheocrenic, or floodplain/riparian hillslope springs emerge from the bank or terrace of a river or stream (distinguished from a true rheocrene spring, which sources on the stream bed). Rheocrenic hillslope springs are subject to regular stream or river flooding, and usually contain wide-spread, flood-tolerant species. Upland hillslope springs are located outside of a riparian setting, are not subject to stream flooding, and commonly support rare species (Fig. 1–21). Anthropogenic subtypes of hillslope springs are also possible; these can be created by pipe or ditch leakage.

Alternate Names and Comments: Seepage area, fracture spring, fissure spring, joint spring, contact spring (Bryan 1919, Meinzer 1923); spring-fed slope wetlands; headwater slope wetlands; high-gradient ciénegas.

Common Stressors: Groundwater extraction, recreation, non-native species introduction, and climate change.

Fig. 1–21. Lemna Tank Spring is a hillslope spring in Elko County, Nevada.

Hypocrene

Definition: At this springs type, shallow groundwater is expressed through wetland vegetation but not as surface emergence or flow (Fig. 1–22 and Fig. 1–23). Hypocrenes occur naturally, but also commonly develop from other springs types as groundwater tables decline through overdraft. In response to the loss of surface water from a previously flowing spring, the plant community shifts from being dominated by aquatic and wetland-obligate species, to dominance by riparian groundwater-dependent species, and ultimately to upland vegetation if the water table continues to decline.

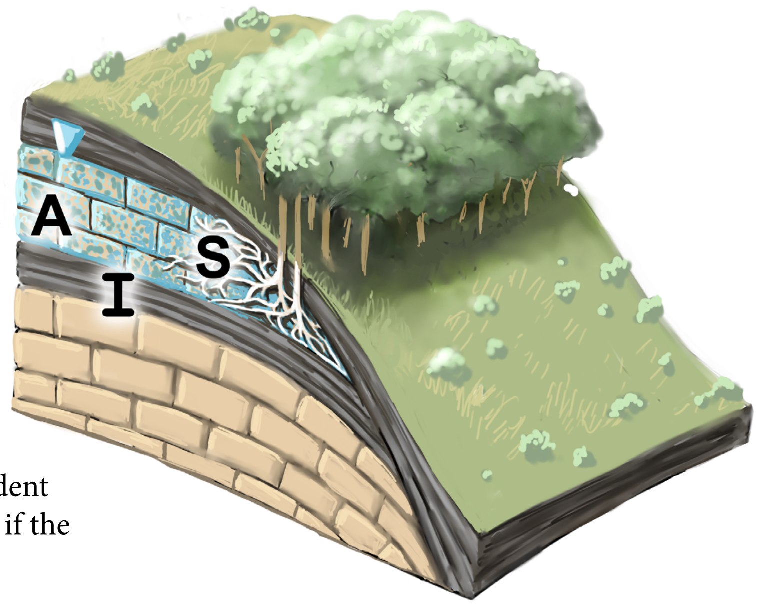

Fig. 1–22. In this illustration of an exposure springs ecosystem, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a springs source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Common Attributes and Secondary Types: Mound-form and rheocrene springs are commonly hypocrene; anthropogenic hypocrene springs are common, due to groundwater depletion.

Alternate Names and Comments: Ephemeral springs; dry springs; Pleistocene lakebed wetlands where groundwater is not expressed at the surface; misinterpreted as terrestrial ecosystems that occasionally rely on groundwater; subsurface presence of groundwater (Eamus and Froend 2006).

Common Stressors: Groundwater depletion, urbanization, livestock grazing, non-native species introduction, and climate change.

Fig. 1–23. McCormick Spring is a hypocrene spring located in Apache-Sitgreaves National Forest, Arizona.

Limnocrene

Definition: : A pool-forming gravity springs ecosystem, forming from a fissure, depression, or contact geologic setting (Fig. 1–24 and Fig. 1–25; Meinzer 1923). Limnocrenes can contain acidic (e.g., some groundwater dependent bogs), or geothermal waters (e.g., Diana's Punchbowl in central NV and other Great Basin geothermal lakes). Prairie potholes are sourced, in part, from groundwater, and are examples of limnocrenes. Ephemeral limnocrenes are also recognized.

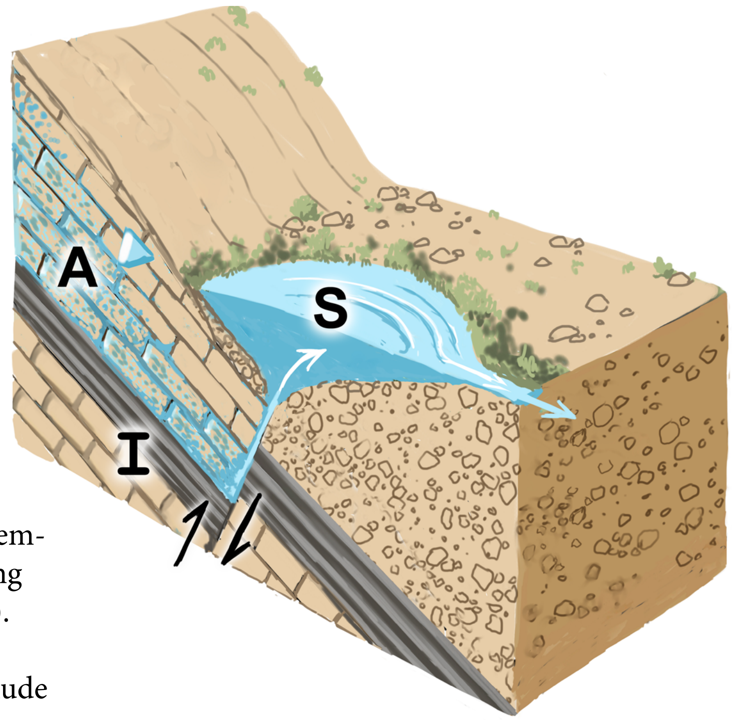

Fig. 1–24. In this illustration of a limnocrene spring, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a springs source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist.

Common Attributes and Secondary Types: Limnocrene springs can be perennial or ephemeral (for example, turloughs, the "disappearing lakes" found in limestone settings in Ireland). Limnocrene paleosprings can sometimes be recognized. Anthropogenic limnocrenes include GDE livestock watering tanks, mine pits, quarries, etc.

Alternate Names and Comments: Depressions, sinkholes (Bryan 1919, Meinzer 1923); lacustrine wetlands or aquatic bed wetlands; GDE ponds, pools, tanks, quarries (anthropogenic), or lakes; acid limnocrenes; prairie potholes (northern Great Plains in North America); perennial GDE pools and lakes. Vernal pools are not considered to be limnocrene springs, because they are sourced from surface water.

Common Stressors: Groundwater depletion, agricultural and mining pollution, urbanization, pond margin habitat alteration, livestock grazing, recreation, non-native species introduction, and climate change.

Fig. 1–25. Grassi Lake is one in a series of pools fed by limnocrene springs in Alberta, Canada.

Mound-form

Definition: Precipitation of secondarily derived carbonates, or accumuulation of organic (peat mound) matter or ice creates a dome form, from which groundwater emerges and usually flows (Fig. 1–26 and Fig. 1–27). Precipitate mounds can form from depression, sinkhole, tubular, fissure, fracture, or joint geologic structures (Bryan 1919, Meinzer 1923);

Common Attributes and Secondary Types: Mound-form springs can be perennial or ephemeral. Subtypes include organic mound, carbonate mound, and ice mound. Secondary springs types often associated with mound-form springs are geyser, fountain, helocrene, limnocrene, and paleosprings.

Alternate Names and Comments: Travertine mound precipitate mound springs; GDE fens in some cases; Pingos, aufeis, or hydrolaccoliths in ice-dominated environments.

Common Stressors: Groundwater depletion; agricultural and mining pollution; urbanization, pond margin habitat alteration, livestock grazing/soil compaction, recreation, non-native species introduction, and climate change.

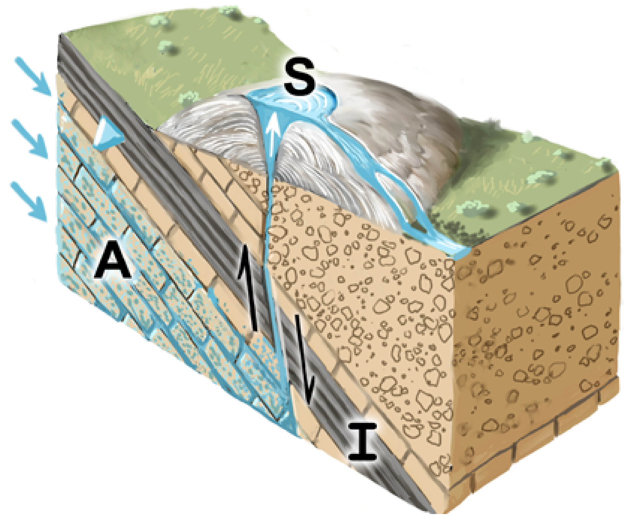

Fig. 1–26. In this illustration of a mound-form spring, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

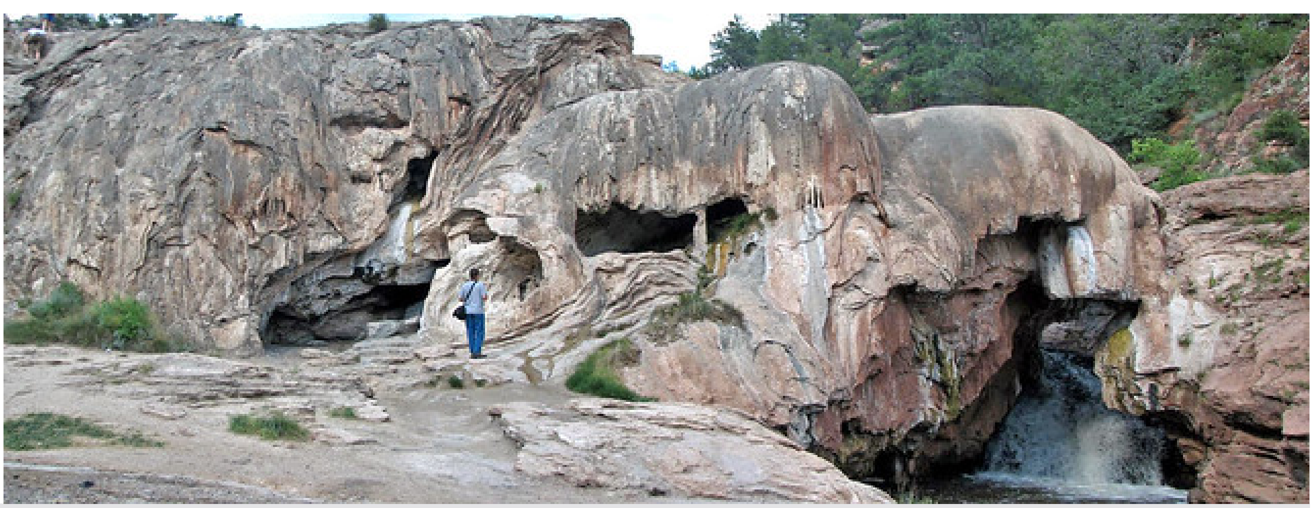

Fig. 1–27. Soda Dam is approximately 7,000 years old. This hot springs travertine mound formed along the Jemez River in northern New Mexico. Photo courtesy of James St. John (Geology, Ohio State University at Newark).

Rheocrene

Definition: Groundwater emergence within an established stream channel (i.e., a surface water runoff or flood channel, where the channel exists upstream of the springs source). Rheocrene springs generally occur because of geologic structural constraints on the groundwater flowpath (Fig. 1–28). This is often visible as the narrowing of a bedrock canyon, which forces groundwater out of floodplain alluvium and into the stream channel. Rheocrene springs are most visible when they emerge into otherwise dry channels, but they can also emerge into perennial streams (Fig. 1–29).

Common Attributes and Secondary Types: Rhythmic springs often are rheocrenes. Common secondary types for rheocrene springs are cave, gushet, hanging garden, helocrene, hillslope, and limnocrene; anthropogenic subtypes are possible as effluent releases and dam tailwater function as rheocrenes.

Alternate Names and Comments: channel or flowing springs, derived from fracture, fissure, contact, or seepage geologic structures (Bryan 1919; Meinzer 1923). Riverine wetlands, streambed wetlands; river base-flow springs, alluvial forest springs. Rhythmic (AKA beating heart, ebb and flow, periodic, pulsing, or siphon) springs may exist as rheocrenes (Huntoon and Coogan 1987).

Common Stressors: Groundwater extraction, livestock water supplies, agricultural hay-mowing, urbanization, road construction (may dewater or divert water from the downslope portion, or alter channel margins), recreation, non-native species introduction, and climate change.

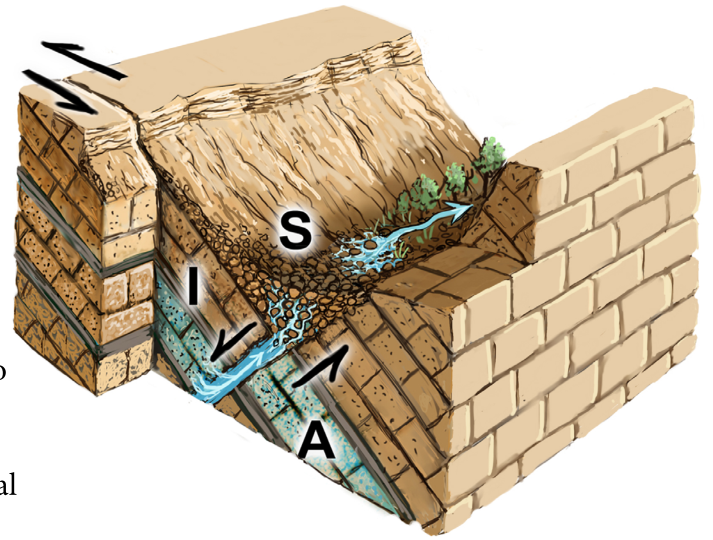

Fig. 1–28. In this illustration of a rheocrene spring, "A" indicates aquifer input, "I" indicates an impermeable layer or aquitard, and "S" indicates a spring source. Image used with permission from Larry Stevens, Museum of Northern Arizona Springs Stewardship Institute, and Victor Lesyk, artist. All rights are reserved.

Fig. 1–29. Flap Spring is a rheocrene spring that emerges into a streambed that runs along the eastern base of the Corduroy Mountains in the White Pine Range, Nevada.

Other Springs Types

Not included in these illustrations are paleosprings that flowed in the recent geologic past (e.g., the Pleistocene or early Holocene), but no longer do so. Paleosprings usually occur as travertine mounds or exposures of fossilized peat.

Springs Distribution by Type

Springs types in Arizona tend to group by physiographic province, with rheocrene and hillslope springs more common in the Basin and Range province, and hanging gardens and gushets more common on the Colorado Plateau. Helocrene springs (wet meadows springs) were once abundant throughout the Southwest, with low elevation ciénegas and higher elevation groundwater-dependent fens. However, due to extensive draining and management for livestock and agriculture, helocrene springs are now among the most critically endangered ecosystem types in the Southwest (Hendrickson and Minckley 1984).

Conclusions

The need for scientific agreement on basic classification of springs remains outstanding, and the absence of that agreement sows confusion among the public and managers who continue to use and manipulate these important and often irreplaceable ecosystems. Nearly all authors on all continents recognize springs biodiversity and socioeconomic importance, and the imperiled nature of springs ecosystems. However, the lack of consensus on springs classification has directly contributed to the lack of public, scientific, and governmental awareness of the importance of springs ecosystems, and the regional, national, and global demise of these important ecosystems (Cantonati et al. 2007; Stevens and Meretsky 2008; EC 2015; Kreamer et al. 2015; Knight 2015).

Springs ecosystem classification based on local geomorphology remains the most logical means of describing springs ecosystems. "Sphere of discharge" geomorphology provides spatially explicit physical description of the springs ecosystem. The other classification approaches are either insufficiently explicit to identify the sites as springs (aquifer, flow, and water quality approaches), insufficiently specific (landform position approaches), or vary over time (biotic, especially aquatic algae and invertebrates, and macrophytic vegetation approaches). A local geomorphological approach also readily lends itself to description of the extent of anthropogenic landscape alteration and provides for spatial quantification of those impacts, data which are useful in stewardship assessment, planning, implementation, and monitoring.